

# **Structural Control Optimisation and Health Monitoring using Newly Developed Techniques**

A thesis submitted in fulfilment  
of the requirements for the degree of  
**Doctor of Philosophy**

By

**Mohsen Askari**



Faculty of Engineering and Information Technology  
University of Technology, Sydney

March, 2014

*To My Beautiful Sister:*

*Raheleh*

## CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Candidate



---

Date

22 March 2014

---

# ACKNOWLEDGMENTS

I am truly fortunate to have spent four years at the Centre for Built Infrastructure Research (CBIR) at University of Technology, Sydney (UTS) that provided me the great opportunity to accomplish my graduate studies in a friendly but highly competitive environment. I would first like to thank my PhD supervisors, Associate Prof. Jianchun Li and Prof. Bijan Samali who guided, mentored and encouraged me throughout my thesis with their knowledge, jovial disposition and patience.

I would like to acknowledge the members of CBIR Dynamics and Control Group, in particular Dr. Yancheng Li for his generous help during my experimental tests and Dr. Amir Ali Zad for his valuable guidelines about student life in UTS and Australia.

I am also indebted to my true friends who gave me so many helps in different ways during my study at UTS. My special thanks go to Dr. Saad Mahbub Subhani, Dr. Yukari Aoki, Dr. Ikram Mohammad Kabir, Dr. Vahid Behbood, Dr. Ali Parsa Pajouh, Alireza Radman, Kianoosh Keynejad, Amir Reza Bahrami, Rowshanak Rahrooh, Mona Parvaresh, Leila & Peyman, Zubin Kalchuri, Tina Nyhammer...

Last, but not the least, I thank my family for their support through my entire life. My special appreciation goes out to my brother Meisam without whose motivation and encouragement, completion of this degree would be impossible.

# LIST OF PUBLICATIONS RELATED TO THIS THESIS

## **Journal Articles**

1. Semi-Active LQG Control of Seismically Excited Nonlinear Buildings using Optimal Takagi-Sugeno Inverse Model of MR Dampers, M Askari, J Li, B Samali, *Procedia Engineering* 14, 2765-2772
2. Cost effective Multi Objective Placement of Actuators and MR Dampers in High-Rise Structures using a Modified Integer Coded NSGAI, M. Askari, B. Samali, J. Li, *Engineering Applications of Artificial Intelligence* (Under Review)
3. Intelligent Semi-Active Control of Building-MR Damper Systems using Novel TSK-Inv and Max-Min Algorithms, M.Askari, J. Li, B. Samali, *Journal of intelligent material systems and structures*, (Revised sent).
4. Application of extended, unscented, iterated extended and iterated unscented Kalman filter for real-time structural identification; an experimental comparison study, M.Askari, J. Li, B. Samali, *International Journal of Structural Stability and Dynamics*, (Under Review)
5. Experimental forward and inverse modelling of MR dampers using an optimal TSK fuzzy scheme M.Askari, J. Li, B. Samali, *Journal of intelligent material systems and structures*, (Revised sent).
6. Adaptive Multiple Forgetting Factor Recursive Least Square (AMFF-RLS) for Real-Time Structural Identification with Unknown Input, *Advances in Structural Engineering*, (Under Review)

**Book Chapter**

7. A Multi-objective Subtractive FCM Based TSK Fuzzy System with Input Selection, and Its Application to Dynamic Inverse Modelling of MR Dampers, M. Askari, J Li, B Samali, *Artificial Intelligence and Soft Computing*, 215-226

**Conference Papers**

8. Adaptive Multiple Forgetting Factor Recursive Least square (AMFF-RLS) for real-time structural identification, M Askari, J Li, B Samali, 22nd ACMSM: “Materials to Structures: Advancement through Innovation”, Sydney, Australia December 2012.
9. Application of extended, unscented, iterated extended and iterated unscented Kalman filter for real-time structural identification, M Askari, J Li, B Samali, 7th Australasian Congress on Applied Mechanics (ACAM 7), Adelaide, December 2012.
10. Adaptive multiple forgetting factor recursive least square (AMFF-RLS) for Real-Time Structural Identification with Unknown Input, M Askari, J Li, B Samali, 7th Australasian Congress on Applied Mechanics (ACAM 7), Adelaide, December 2012.
11. Multi Objective Optimal Placement of Structural Control Actuators, M Askari, 6th Australasian Congress on Applied Mechanics (ACAM 6), Perth, December 2010.
12. Future Intelligent Civil Structures: Challenges and Opportunities, J. Li, Y. Li, M. Askari, QP. Ha, The International Symposium on Automation and Robotics in Construction and Mining (ISARC 2014), Sydney, July 2014

# TABLE OF CONTENTS

<b>CERTIFICATE OF AUTHORSHIP/ORIGINALITY.....</b>	<b>I</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>II</b>
<b>TABLE OF CONTENTS.....</b>	<b>V</b>
<b>LIST OF FIGURES .....</b>	<b>IX</b>
<b>LIST OF TABLES .....</b>	<b>XIII</b>
<b>ABSTRACT .....</b>	<b>XIV</b>
<b>CHAPTER 1 .....</b>	<b>1</b>
<b>INTRODUCTION.....</b>	<b>1</b>
1.1 Motivation for this research .....	4
1.2 Objectives of the present research .....	6
1.3 Organisation of the thesis .....	7
<b>CHAPTER 2 .....</b>	<b>10</b>
<b>MR DAMPER MODELLING .....</b>	<b>10</b>
2.1 Chapter Outline.....	10
2.2 Introduction and Background .....	10
2.2.1 Magnetorheological Dampers .....	10
2.2.2 Forward Models of a MR Damper .....	12
2.2.3 Non-parametric models .....	16
2.2.4 Inverse Models of a MR Damper .....	17
2.3 A new non-parametric approach for MR damper Modelling.....	17
2.3.1 Preliminaries .....	19
2.3.1.1 TSK Fuzzy Structure .....	19
2.3.1.2 Scatter Partitioning .....	20
2.3.1.3 Subtractive Clustering .....	21
2.3.1.4 FCM based TSK model identification .....	21
2.3.1.5 Non-Dominated Sorting Genetic Algorithm II (NSGA II) .....	23
2.3.2 Proposed Hybrid Learning Algorithm.....	25
2.3.2.1 Genetic Encoding Scheme.....	25
2.4 Inverse Model of MR Damper (Numerical Study) .....	27
2.4.1 Data Collection.....	27
2.4.2 Numerical Results .....	28
2.4.3 Model validation .....	30

2.5 MR Damper Modelling (Experimental Study) .....	32
2.5.1 Experimental Data collection for Training and Validation .....	36
2.5.2 Forward model of MR damper (experimental study) .....	37
2.5.3 Inverse model of MR damper (experimental study) .....	39
2.6 Summary .....	43
<b>CHAPTER 3 .....</b>	<b>47</b>
<b>MULTI-OBJECTIVE OPTIMAL PLACEMENT OF STRUCTURAL</b>	
<b>CONTROL DEVICES.....</b>	<b>47</b>
3.1 Chapter Outline .....	47
3.2 Introduction and Background .....	48
3.3 Modified Integer-Coded NSGAI .....	52
3.3.1 Laplace Crossover .....	53
3.3.2 Power Mutation .....	53
3.3.3 Truncation procedure for integer adjustable parameters .....	54
3.4 The proposed MI-NSGAI based approach to find the optimal numbers and places of control devices .....	54
3.5 Case Study: 20-Storey Nonlinear Benchmark Structure .....	57
3.5.1 Optimal Number and Places of Active Actuators .....	58
3.5.2 Optimal MR Damper Number and Places .....	66
3.6 Summary .....	71
<b>CHAPTER 4 .....</b>	<b>79</b>
<b>OPTIMAL SEMI-ACTIVE CONTROL OF NONLINEAR MR DAMPER-</b>	
<b>BUILDING SYSTEMS .....</b>	<b>79</b>
4.1 Chapter Outline .....	79
4.2 Introduction and Background .....	80
4.2.1 Control Based on Lyapunov Stability Theory .....	81
4.2.2 Decentralised Bang-Bang Control .....	82
4.2.3 Maximum Energy Dissipation .....	83
4.2.4 Modulated Homogeneous Friction .....	84
4.2.5 Clipped-Optimal Control .....	86
4.2.6 Modified Clipped-Optimal Control .....	88
4.2.7 Signum Function Controller .....	89
4.2.8 Soft Computing Based Control .....	91
4.3 Case Study: 3 <sup>rd</sup> Generation 20-Storey Nonlinear Benchmark Building .....	92
4.4 Proposed Control Strategies .....	93
4.4.1 Primary Controller and Kalman Filter Observer Design .....	94
4.4.2 Voltage Controller 1: Optimal TSK Fuzzy Inverse Controller (TSKFInv) .....	97
4.4.2.1 Forward Model of 1,000 kN MR Damper using Acceleration Feedback Only .....	97



4.4.2.2 Inverse Model of 1,000 kN MR damper Model .....	99
4.4.3 Voltage Controller 2: Max-Min Optimal Controller .....	101
4.5 Numerical results .....	102
4.6 Summary .....	113
<b>CHAPTER 5 .....</b>	<b>121</b>
<b>ONLINE REAL-TIME STRUCTURAL IDENTIFICATION .....</b>	<b>121</b>
5.1 Chapter Outline .....	121
5.2 Introduction and background .....	122
5.2.1 Parametric Methods .....	125
5.2.2 Non-parametric Methods .....	129
5.2.3 Final Statements on the literature .....	130
5.3 Kalman Filtering Methods .....	131
5.3.1 Principles of EKF, IEKF, UKF and IUKF .....	134
5.3.1.1 Extended Kalman Filter (EKF) .....	134
5.3.1.2 Iterated Extended Kalman Filter (IEKF) .....	135
5.3.1.3 Unscented Kalman Filter (UKF) .....	136
5.3.1.4 Iterated Unscented Kalman Filter (IUKF) .....	138
5.3.2 Numerical Simulations .....	140
5.3.2.1 SDOF nonlinear hysteretic system .....	140
5.3.2.2 2DOF linear structural system .....	144
5.4 Recursive Least Square Based Methods .....	149
5.4.1 Recursive least square with adaptive multiple forgetting factor and known inputs (AMFF-RLS) .....	150
5.4.2 Recursive least square with adaptive multiple forgetting factor and unknown inputs (AMFF-RLS-UI) .....	154
5.4.3 Numerical Simulations .....	157
5.4.3.1 SDOF nonlinear hysteretic system .....	157
5.4.3.2 2DOF linear structural system .....	161
5.4.3.3 3DOF linear structural system with unknown excitation on top floor .....	165
5.5 Summary .....	167
<b>CHAPTER 6 .....</b>	<b>170</b>
<b>CONCLUSIONS AND FUTURE RESEARCH .....</b>	<b>170</b>
6.1 MR Damper Modelling .....	170
6.2 Multi-Objective Optimal Placement of Structural Control Devices .....	171
6.3 Semi-Active Control of MR Damper Building Systems .....	173
6.4 Online Real-Time Structural Identification .....	175
6.5 Future Research .....	177

---

<b>REFERENCES.....</b>	<b>182</b>
<b>APPENDICES .....</b>	<b>197</b>
<b>APPENDIX A: STRUCTURAL EVALUATION CRITERIA .....</b>	<b>197</b>
<b>APPENDIX B: EARTHQUAKE SIGNALS.....</b>	<b>200</b>
<b>APPENDIX C: STRUCTURAL RESPONSE OF UNCONTROLLED 20- STOREY NONLINEAR BENCHMARK BUILDING.....</b>	<b>201</b>

# LIST OF FIGURES

Figure 1.1. Kobe earthquake, 1995, Japan .....	2
Figure 2.1. A schematic of the prototype 20-ton large-scale MR damper (Yang et al. 2002) ...	12
Figure 2.2. Bingham model of an ER/MR damper (Stanway, Sproston & Stevens 1985) .....	13
Figure 2.3. Bouc-Wen model of the MR Damper (Spencer et al. 1997) .....	14
Figure 2.4. Modified Bouc-Wen model of the MR Damper (Spencer et al. 1997) .....	16
Figure 2.5. Structure of a TSK Fuzzy Model (r: number of inputs; k: number of rules) .....	18
Figure 2.6. Non-Dominated Sorting Concept .....	24
Figure 2.7. Encoding scheme for individual chromosomes .....	25
Figure 2.8. Collected Data (Inverse model, Numerical study) .....	29
Figure 2.9. Pareto Front for Inverse Model of MR Damper (numerical study) .....	29
Figure 2.10. Block diagram for the inverse model validation strategy of MR damper .....	30
Figure 2.11. The comparison between the target and generated voltage .....	31
Figure 2.13. Numerical Validation data .....	32
Figure 2.12. The comparison between the target and generated force .....	31
Figure 2.14. Comparison between the predicted and target voltages and forces .....	32
Figure 2.15. MR damper test on Schenck material testing machine .....	33
Figure 2.16. MR damper installation .....	34
Figure 2.17. Input excitation for MR damper testing: sinusoidal and quasi static excitations ..	35
Figure 2.18. Training data (Inverse model, experimental study) .....	36
Figure 2.19. Pareto Front for Forward Model of MR damper (experimental study) .....	38
Figure 2.20. Comparison between original and predicted force of MR damper forward model (experimental study, training data) .....	38
Figure 2.21. Validation data set (forward Model, experimental data) .....	39
Figure 2.22. Comparison between predicted and target force (Forward model, experimental data) .....	40
Figure 2.24. Comparison between target and predicted current of MR damper inverse model (experimental study, training data) .....	41
Figure 2.23. Pareto Front for inverse modelling of MR damper (experimental study) .....	41
Figure 2.25. Comparison between target and generated force using MR damper inverse model (experimental study, training data) .....	43
Figure 2.26. Comparison between target and generated force using inverse model of MR damper (Experimental validation data, case 42) .....	44

Figure 2.27. Comparison between target and generated force using inverse model of MR damper (Experimental validation data, case 28).....	45
Figure 2.28. Comparison between target and generated force using inverse model of MR damper (Experimental validation data, case 14).....	46
Figure 3.1. Proposed Optimisation Flowchart .....	56
Figure 3.2 Encoding scheme for individual chromosome .....	57
Figure 3.3. 20 -Storey benchmark building proposed in this study .....	59
Figure 3.4 Pareto Fronts Obtained for Optimal Places of Different Number of Actuators .....	62
Figure 3.5 Pareto Front for optimal placement of 15 and 25 actuators.....	63
Figure 3.6 Optimal Actuator Placement in 20-storey benchmark structures for different purposes .....	64
Figure 3.7 Changes of Performance Indices vs. Number of Actuators (Trade-Off Scenario)...	65
Figure 3.8 Block diagram of the proposed semi-active control algorithm.....	67
Figure 3.9. Pareto Fronts for optimal assignment of different number of MR dampers.....	69
Figure 3.10. Pareto Fronts for optimal assignment of different number of MR dampers (Continue) .....	70
Figure 3.11. Optimal MR Dampers Placement in 20-storey benchmark structure .....	73
Figure 3.12. Changes of Performance Indices vs. Number of MR dampers (Trade-Off Scenario) .....	74
Figure 3.13. Comparison of peak floor displacement and acceleration with and without optimisation.....	75
Figure 3.14. Structural Performance for Optimal Assignments of actuators and MR dampers	76
Figure 4.1. Typical desired control force produced with the Modulated Homogeneous Friction algorithm.....	86
Figure 4.2. Graphical representation of clipped-optimal control algorithm. ....	87
Figure 4.3. Graphical representation of modified clipped-optimal control algorithm. ....	88
Figure 4.4. Graphical representation of vSign1 ( $N = 6$ , $k < 0$ , $f_c > 0$ , $f > 0$ ): (a) $f_c \gg f$ and $vSign1 = V_{max}$ ; (b) $f_c \approx f$ and $vSign1 = 2/3 V_{max}$ ; and (c) $f_c \ll f$ and $vSign1 = 0$ .....	90
Figure 4.5. Graphical representation of vSign2 provided that the condition $vSign1 \geq V_{max}$ is satisfied: (a) if $ff < 0$ , then $vSign2 = 0$ , $vSign2 = 0 (=V_{min})$ and (b) if $ff > 0$ , then $vSign2 = 1$ , $vSign = vSign1$ . ....	90
Figure 4.6. MR damper and accelerometer configurations.....	93
Figure 4.7. Block diagram of semi-active control strategy .....	94
Figure 4.8. TSK Fuzzy inverse optimal controller.....	98
Figure 4.9. Pareto front of forward model of MR damper.....	99
Figure 4.10. Pareto front of inverse model of MR damper .....	100

Figure 4.11. Comparison between target and predicted voltage (Hann et al.) and target and predicted force (bottom) using fuzzy inverse and forward models of MR damper .....	100
Figure 4.12. Schematic diagram of MaxMin optimal controller (proposed in this study).....	102
Figure 4.13. MR damper's force and voltage at 20 <sup>th</sup> floor (El-Centro, intensity: 1.0).....	104
Figure 4.14. MR damper's force and voltage at 20 <sup>th</sup> floor (Hachinohe, intensity:1.0) .....	105
Figure 4.15. MR damper's force and voltage at 20 <sup>th</sup> floor (Northridge, intensity:1.0).....	106
Figure 4.16. MR damper's force and voltage at 20 <sup>th</sup> floor (Kobe, intensity:1.0).....	107
Figure 4.17. Structural control force and power comparison between different semi-active control algorithms .....	112
Figure 4.18. Performance criteria (worse case scenario) .....	114
Figure 4.19. Structural Response (El-Centro, 0.5).....	116
Figure 4.20. Structural Response (El-Centro, 1.0).....	116
Figure 4.21. Structural Response (El-Centro, 1.5).....	117
Figure 4.22. Structural Response (Hachinohe, 0.5) .....	117
Figure 4.23. Structural Response (Hachinohe, 1.0) .....	118
Figure 4.24. Structural Response (Hachinohe, 1.5) .....	118
Figure 4.25. Structural Response (Northridge, 0.5).....	119
Figure 4.26. Structural Response (Northridge, 1.0).....	119
Figure 4.27. Structural Response (Kobe, 0.5).....	120
Figure 4.28. Structural Response (Kobe, 1.0).....	120
Figure 5.1. Example of mean and covariance propagation (Julier & Uhlmann 1997).....	133
Figure 5.2. SDOF nonlinear hysteretic system .....	142
Figure 5.3. Parameters estimation for SDOF nonlinear system, noise level 2% RMS. ....	143
Figure 5.4. Estimated hysteretic loops for the Bouc–Wen system, noise level 2% RMS.....	144
Figure 5.5. 2DOF linear system.....	145
Figure 5.6. Parameters estimation for 2-DOF linear system, noise level 1% RMS and $X_0 = [0.0001, 0.0001, 0.0001, 0.0001, 5, 5, 0.3, 0.3]$ .....	147
Figure 5.7. Parameters estimation for 2-DOF linear system, noise level 5% RMS, and $X_0 = [0.0001, 0.0001, 0.0001, 0.0001, 2.8, 2.8, 0.15, 0.15]$ . ....	148
Figure 5.8. Identified results for an SDOF system (case 1) .....	159
Figure 5.9. Identified results for a SDOF system (case 2) .....	160
Figure 5.10. Identified unknown earthquake acceleration for the SDOF system (case 2).....	160
Figure 5.11. Identified parameters for 2DOF system with known input (case 1).....	162
Figure 5.12. Identified parameters for 2DOF system with unknown input (case 1).....	162
Figure 5.13. Identified unknown earthquake acceleration for the 2DOF system (case 1) .....	163

---

Figure 5.14. Identified results for a 2DOF system with known input, using RLS with single forgetting factor of 0.95 (case 1).....	163
Figure 5.15. The forgetting factor obtained for the stiffness of the second storey (Case 1)....	164
Figure 5.16. Identified results for a 2DOF system (case 2) .....	165
Figure 5.17. Identified unknown earthquake acceleration for a 2DOF system (case 2) .....	165
Figure 5.18. Identified parameters for 3DOF system .....	168
Figure 5.19. Identified external input, on top floor for 3DOF system .....	169
Figure 5.20. The forgetting factor obtained for the stiffness of the first storey .....	169
Figure 6.1. A Shear Structure (Left), The two-storey standard substructure (right).....	179
Figure 6.2. Integration of SHM and SC (Chen & Xu 2008) .....	181

# LIST OF TABLES

Table 2-1. Typical Parameters of a 1000kN MR Damper .....	28
Table 2-2. GA parameters used in inverse MR damper Modelling optimisation (Numerical)..	29
Table 2-3. MR damper testing conducted for 42 operating conditions.....	35
Table 2-4. GA parameters used in forward MR damper Modelling optimisation .....	37
Table 2-5. GA parameters used in inverse MR damper modelling optimisation.....	39
Table 3-1. GA parameters used in actuators distribution optimisation.....	61
Table 3-2. GA parameters used in MR dampers distribution optimisation .....	68
Table 3-3. Optimal Actuator Placements .....	77
Table 3-4. Optimal MR Damper Placements .....	78
Table 4-1. Structural evaluation criteria .....	108
Table 4-2. Computational effort comparison between different control algorithms for 20 seconds of El-Centro earthquake with intensity of 1 .....	113
Table 5-1. Estimation results for the 2DOF linear system .....	149
Table 5-2. RLS based method feature comparison .....	155

# ABSTRACT

Vibration is usually undesirable and yet it occurs in most machines, vehicles, structures, buildings and dynamic systems. The resulting unpleasant motions and the dynamic stresses may lead to fatigue and failure of the structure or machines. In the field of civil engineering, control and identification of the state of health of the structure during the dynamic loads, such as earthquakes and attempt to suppress the vibrations and detect any damage or potential hazard are of vital importance and have posed a great challenge to the research community.

This thesis presents new techniques for optimisation, real-time health monitoring and semi-active vibration control of structures subjected to seismic loads.

First, a new encoding scheme is presented for a fuzzy-based nonlinear system identification methodology, using subtractive Fuzzy C-Mean clustering and non-dominated sorting genetic algorithm. The method is able to automatically select the best inputs as well as the structure of the fuzzy model in such a way that both accuracy and compactness of model are guaranteed. The proposed method is then employed to identify the forward and inverse models of a MR damper. Numerical and Experimental results show that the developed evolving TSK fuzzy model can identify and grasp the nonlinear dynamics of both forward and inverse systems very well, while a small number of inputs and fuzzy rules are required for this purpose.

The optimal design and placement of control devices, is an important problem that affects the control of civil engineering structures. This study also presents a multi-objective optimisation method for simultaneous finding of optimal number and location of actuators and MR dampers, in active and semi-active controlled structures. The method is applied to a nonlinear 20-storey benchmark building. The obtained optimal layout of active actuators is compared to the original benchmark problem definition in which 25 actuators are located in non-optimal places. Results show the effect of proposed strategy where similar level of structural performance, in terms of proposed objective indices, is achieved by use of only 7 actuators in optimal locations. Also, the



optimal configuration of different number of MR dampers in the same nonlinear benchmark building is also studied. Results are then compared with optimal locations of actuators in the equivalent active system and the differences are shown.

Two new semi-active control algorithms named TSKInv and MaxMin, are also introduced in this research study to convert the force generated by nominal controller to the required voltage of MR dampers. TSKInv algorithm is developed by modelling the inverse dynamics of MR damper using TSK fuzzy inference systems and MaxMin controller is designed based on the maximum (*maximum voltage*) and minimum (*minimum voltage*) load of MR damper at each time-step. Applications of these two newly developed methods are compared to some other semi-active control strategies through the 20-storey nonlinear benchmark building. Results show the superiority of these two models over the other algorithms in tracking the desired force using less amount of control force and power.

Also, an investigation on different Kalman Filtering algorithms used in system identification is carried out in this dissertation work, on which EKF, IEKF, UKF and IUKF have been applied to some numerical examples to estimate the parameters of targeted structures in real-time using acceleration responses only. Results demonstrate that IUKF and UKF are the most reliable and robust estimators even if the structure is highly nonlinear and measured data are contaminated with noise. Then, a novel recursive least square based method with adaptive multiple forgetting factor is proposed and applied to different structural identification problems with unknown excitations. It is found from the results that, the proposed algorithm can effectively identify the time-varying parameters as well as the unknown inputs to the structure with high computational efficiency.

Using the developed techniques, this project aims to prepare a platform for real-time structural integrity assessment of civil infrastructures, during or after earthquakes.